CLAIMS

1. An ion transport membrane system comprising

(a) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of planar ion transport membrane modules disposed in the interior of the pressure vessel and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(c) one or more gas manifolds in flow communication with interior regions of the membrane modules and with the exterior of the pressure vessel.

2. The system of Claim 1 wherein each planar membrane module comprises a plurality of wafers having planar parallel surfaces, and wherein the pressure vessel is cylindrical and has an axis that is parallel to some or all of the planar parallel surfaces of the wafers.

3. The system of Claim 1 which further comprises a flow containment duct disposed in the interior of the pressure vessel, wherein the flow containment duct surrounds the plurality of planar ion transport membrane modules and is in flow communication with any inlet and any outlet of the pressure vessel.

4. The system of Claim 3 wherein

(1) the one or more gas manifolds comprise an inlet manifold and an outlet manifold;

(2) the interior region of any planar membrane module is in flow communication with the inlet manifold via a secondary inlet manifold and is in flow communication with the outlet manifold via a primary outlet manifold; and

(3) within the flow containment duct, the secondary inlet manifold and the primary outlet manifold of any planar membrane module are combined to form a nested manifold.

5. The system of Claim 3 wherein the flow containment duct comprises an oxidation-resistant metal alloy containing iron and one or more elements selected from the group consisting of nickel and chromium.

6. The system of Claim 1 wherein the one or more gas manifolds are disposed in the interior of the pressure vessel.

7. The system of Claim 1 wherein the one or more gas manifolds are disposed exterior to the pressure vessel.

8. The system of Claim 1 wherein the one or more gas manifolds are insulated internally, externally, or internally and externally.

9. The system of Claim 1 wherein at least two of the planar ion transport membrane modules define a module axis, and wherein the pressure vessel is cylindrical and has an axis that is parallel to the module axis.

10. The system of Claim 1 wherein at least two of the planar ion transport membrane modules define a module axis, and wherein the pressure vessel is cylindrical and has an axis that is perpendicular to the module axis.

11. The system of Claim 1 which further comprises insulation disposed in the interior of the pressure vessel.

12. The system of Claim 11 wherein the insulation is disposed in a region between an interior surface of the pressure vessel and the membrane modules, wherein the insulation forms a cavity that surrounds the membrane modules and the cavity is in flow communication with any inlet and any outlet of the pressure vessel.

13. The system of Claim 12 wherein the insulation is in contact with the interior surface of the pressure vessel.

14. The system of Claim 12 wherein the insulation is not in contact with the interior surface of the pressure vessel.

15. The system of Claim 11 which further comprises a flow containment duct disposed in the interior of the pressure vessel, wherein the planar ion transport membrane modules are disposed within the duct, and wherein the insulation is disposed between an interior surface of the pressure vessel and an exterior surface of the duct.

16. The system of Claim 15 wherein the insulation

(a) is in contact with the interior surface of the pressure vessel and is not in contact with the exterior surface of the duct; or

(b) is in contact with the interior surface of the pressure vessel and is in contact with the exterior surface of the duct; or

(c) is not in contact with the interior surface of the pressure vessel and is not in contact with the exterior surface of the duct; or

(d) is not in contact with the interior surface of the pressure vessel and is in contact with the exterior surface of the duct.

17. The system of Claim 11 which further comprises a flow containment duct disposed in the interior of the pressure vessel and in flow communication with the inlet and outlet of the pressure vessel, wherein the planar ion transport membrane modules are disposed within the duct, wherein the insulation is disposed between an interior surface

of the duct and the membrane modules, and wherein the insulation forms a cavity that surrounds the membrane modules and is in flow communication with any inlet and any outlet of the pressure vessel.

18. The system of Claim 11 which further comprises insulation around the exterior of the pressure vessel.

19. The system of Claim 11 wherein the one or more gas manifolds comprise metal and the ion transport modules comprise ceramic, wherein connections between the one or more gas manifolds and the modules comprise ceramic-to-metal seals, and wherein the ceramic-to-metal seals are surrounded by the insulation.

20. The system of Claim 11 wherein the insulation comprises one or more materials selected from the group consisting of fibrous alumina, fibrous alumina silicate, porous alumina, porous alumina silicate.

21. The system of Claim 11 wherein the insulation comprises one or more materials selected from the group consisting of magnesium oxide, calcium oxide, copper oxide, calcium carbonate, sodium carbonate, strontium carbonate, zinc oxide, strontium oxide, and alkaline-earth-containing perovskites.

22. The system of Claim 1 which further comprises a guard bed disposed between any inlet of the pressure vessel and a first membrane module.

23. The system of Claim 22 wherein the guard bed contains one or more materials selected from the group consisting of magnesium oxide, calcium oxide, copper oxide, calcium carbonate, sodium carbonate, strontium carbonate, zinc oxide, strontium oxide, and alkaline-earth-containing perovskites.

24. The system of Claim 1 which further comprises

(a) one or more additional pressure vessels, each having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of planar ion transport membrane modules disposed in the interior of each of the one or more pressure vessels and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(c) one or more gas manifolds in flow communication with interior regions of the membrane modules and with the exterior of the pressure vessel;

wherein at least two of the pressure vessels are arranged in series such that the outlet of one pressure vessel is in flow communication with the inlet of another pressure vessel.

25. The system of Claim 1 which further comprises

(a) one or more additional pressure vessels, each having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of planar ion transport membrane modules disposed in the interior of each of the one or more pressure vessels and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(c) one or more gas manifolds in flow communication with the interior regions of the membrane modules and with the exterior of the pressure vessel;

wherein at least two of the pressure vessels are arranged in parallel such that any inlet of one pressure vessel and any inlet of another pressure vessel are in flow communication with a common feed conduit.

26. The system of Claim 1 which further comprises an additional plurality of planar ion transport membrane modules disposed in the interior of the pressure vessel and arranged in series, wherein the plurality of planar ion transport membrane modules and the additional plurality of planar ion transport membrane modules lie on parallel axes.

27. An ion transport membrane system comprising

(a) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of planar ion transport membrane modules disposed in the interior of the pressure vessel and arranged in a series of banks of modules, each bank containing two or more modules in parallel, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(c) one or more gas manifolds in flow communication with interior regions of the membrane modules and with the exterior of the pressure vessel.

28. An ion transport membrane system comprising

(a) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of ion transport membrane modules disposed in the interior of the pressure vessel and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(c) one or more gas manifolds disposed in the interior of the pressure vessel and in flow communication with the interior regions of the membrane modules and with the exterior of the pressure vessel.

29. An ion transport membrane system comprising

(a) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(b) a membrane stack or module assembly disposed in the interior of the pressure vessel, the assembly having a plurality of planar wafers comprising mixed metal oxide ceramic material, each wafer having an interior region and an exterior region, and a plurality of hollow ceramic spacers, wherein the stack or module assembly is formed by alternating wafers and spacers such that the interiors of the wafers are in flow communication via the hollow spacers, the wafers are oriented parallel to one another, and the alternating spacers and wafers are oriented coaxially to form the stack or module such that the wafers are perpendicular to the stack or module axis;

(c) a gas manifold shroud assembly disposed around the membrane stack or module assembly within the interior of the pressure vessel, wherein the shroud assembly separates the stack or module into at least a first wafer zone and a second wafer zone, places any inlet of the pressure vessel in flow communication with exterior regions of the wafers in the first wafer zone, and places exterior regions of the wafers in the first wafer zone in series flow communication with exterior regions of the wafers of the second wafer zone.

30. The ion transport membrane system of Claim 28 which further comprises a plurality of additional wafer zones formed by the gas manifold shroud assembly, wherein the shroud assembly places the additional wafer zones in series flow communication with one another, and wherein one of the additional wafer zones is in flow communication with any outlet of the pressure vessel.

31. A method for the recovery of oxygen from an oxygen-containing gas comprising

(a) providing an ion transport membrane separator system comprising

(1) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(2) a plurality of planar ion transport membrane modules disposed in the interior of the pressure vessel and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(3) one or more gas manifolds in flow communication with the interior regions of the membrane modules and with the exterior of the pressure vessel;

(b) providing a heated, pressurized oxygen-containing feed gas stream, introducing the feed gas stream via any pressure vessel inlet to the exterior regions of the membrane modules, and contacting the feed gas stream with the mixed metal oxide ceramic material;

(c) permeating oxygen ions through the mixed metal oxide ceramic material, recovering high purity oxygen gas product in the interior regions of the membrane modules, and withdrawing the high purity oxygen gas product from the interior regions of the membrane modules through the gas manifolds to the exterior of the pressure vessel; and

(d) withdrawing an oxygen-depleted oxygen-containing gas from any pressure vessel outlet.

32. The method of Claim 31 wherein the pressure of the oxygen-containing feed gas is greater than the pressure of the high purity oxygen gas product.

33. The method of Claim 31 wherein the ion transport membrane separator system further comprises a flow containment duct that has an interior and an exterior and is disposed in the interior of the pressure vessel, and wherein the flow containment duct surrounds the plurality of planar ion transport membrane modules and is in flow communication with any inlet and any outlet of the pressure vessel such that the oxygen-containing feed gas passes through the interior of the flow containment duct.

34. The method of Claim 33 wherein the pressure differential between the interior and the exterior of the flow containment duct at any point between the inlet and outlet of the pressure vessel is maintained at a value equal to or greater than zero, and wherein the pressure in the interior of the duct is equal to or greater than the pressure in the pressure vessel exterior to the duct.

35. An oxidation process comprising

(a) providing an ion transport membrane reactor system comprising

(1) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(2) a plurality of planar ion transport membrane modules disposed in the interior of the pressure vessel and arranged in series, each membrane module comprising mixed metal oxide ceramic material and having an interior region and an exterior region, wherein any inlet and any outlet of the pressure vessel are in flow communication with exterior regions of the membrane modules; and

(3) one or more gas manifolds in flow communication with interior regions of the membrane modules and with the exterior of the pressure vessel;

(b) providing a heated, pressurized reactant feed gas stream, introducing the reactant feed gas stream via any pressure vessel inlet to the exterior regions of the membrane modules;

(c) providing an oxygen-containing oxidant gas to the interior regions of the membrane modules, permeating oxygen ions through the mixed metal oxide ceramic material, reacting oxygen with components in the reactant feed gas stream in the exterior regions of the membrane modules to form oxidation products therein, and withdrawing the oxidation products from the exterior regions of the membrane modules through any outlet to the exterior of the pressure vessel to provide an oxidation product stream; and

(d) withdrawing oxygen-depleted oxygen-containing gas from the interior regions of the membrane modules via the one or more manifolds to the exterior of the pressure vessel.

36. The process of Claim 35 wherein the pressure of the pressurized reactant feed gas stream is greater than the pressure of the oxygen-containing oxidant gas.

37. The process of Claim 35 wherein the ion transport membrane reactor system further comprises a flow containment duct that has an interior and an exterior and is disposed in the interior of the pressure vessel, and wherein the flow containment duct surrounds the plurality of planar ion transport membrane modules and is in flow communication with the inlet and the outlet of the pressure vessel such that the pressurized reactant feed gas stream passes through the interior of the flow containment duct.

38. The process of Claim 37 wherein the pressure differential between the interior and the exterior of the flow containment duct at any point between the inlet and outlet of the pressure vessel is maintained at a value equal to or greater than zero, and wherein the pressure in the interior of the duct is equal to or greater than the pressure in the pressure vessel exterior to the duct.

39. The process of Claim 35 wherein the pressurized reactant feed gas stream comprises one or more hydrocarbons having one or more carbon atoms.

40. The process of Claim 39 wherein the pressurized reactant feed gas stream comprises methane.

41. The process of Claim 40 wherein the oxidation product stream comprises hydrogen and carbon oxides.

42. An ion transport membrane reactor system comprising

(a) a pressure vessel having an interior, an exterior, an inlet, and an outlet;

(b) a plurality of ion transport membrane modules disposed in the interior of the pressure vessel, wherein a first plurality of modules are arranged in series; and

(c) catalyst disposed between any two membrane modules in the first plurality of modules.

43. The reactor system of Claim 42 which further comprises a second plurality of modules arranged in series, wherein the first plurality of modules is arranged in parallel with the second plurality of modules.

44. The reactor system of Claim 43 wherein the catalyst is disposed between any modules that are arranged in parallel, between any modules that are arranged in series, or between any modules that are arranged in parallel and between any modules that are arranged in series.

45. The reactor system of Claim 44 wherein the catalyst comprises one or more metals or compounds containing metals selected from the group consisting of nickel, cobalt, platinum, gold, palladium, rhodium, ruthenium, and iron.

46. The reactor system of Claim 44 wherein the catalyst is placed between a number of modules in series and the activity of the catalyst varies at different locations between the modules in series.